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# Infants' ability to extract three-dimensional shape from coherent motion

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ABSTRACT

Our capacity to perceive three-dimensional (3D) object structure from two-dimensional (2D) retinal input is fundamental to object perception. The present research examined infants' ability to extract 3D form from structure-from-motion (SFM) displays using a familiarization/visual-paired-comparison paradigm. In SFM displays dots are projected onto the surfaces of a shape that rotates around a 3D axis and it is the coherent structure of the dots' motion that gives rise to the percept of shape. Infants mean age 4.5 and 9 months were familiarized to a SFM display (e.g., cylinder); in test they were presented the familiar SFM display paired with a novel SFM display (e.g., cube). Infants in both age groups displayed a significant preference for the novel SFM test display. These results are consistent with those obtained previously using habituation paradigms and provide converging evidence for infants' early emerging capacity to use coherent motion – in the absence of figural information – as a cue to depth structure. In addition, these results demonstrate that infants' ability to extract 3D shape from coherent motion can be successfully assessed with a neuroimaging-friendly protocol, which was one of the goals of this study.



## 1. Introduction

Our perception of the 3-diminsional (3D) visual world is determined by a complex set of processes that take 2-dimensional (2D) retinal input and transpose it into 3D visual images. Depth structure can be extracted from a variety of visual cues that can be roughly grouped into three types: motion-carried, binocular disparity, and pictorial. There is a rich history of research investigating the conditions under which mature observers draw on these cues to extract the 3D structure of surfaces and objects in the spatial array. In addition, developmental scientists have a long-standing interest in the origins and development of this capacity. A large portion of this research has focused on infants' use of motion-carried information to extract depth structure, an ability that appears to emerge early in the first year (e.g., Arterberry, Craton, & Yonas, 1993; Arterberry & Yonas, 2000; Yonas, Arterberry, & Granrud, 1987).

### 1.1. *Previous research*

One well-documented finding is that infants use common motion to interpret displays containing partly occluded objects. For example, infants 2–4 months perceive pieces of a rod that extend above and below a block as belonging to a single rod connected behind the block, but only when the rod pieces are aligned and share a common motion (Johnson, 2004; Kellman, 1984; Kellman & Spelke, 1983). This percept has been obtained with 3D stimuli (real rods and blocks) and 2D stimuli

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(videotapes or animated displays of 3D objects) and can be attributed to common motion and not other depth cues, such as binocular disparity, motion parallax, or accretion and deletion (Johnson, 2000). Infants also use motion-carried information to segregate 2D surfaces. For example, 2-month-olds use the relative motion of grouped elements against a static background to parse surface area into components (Johnson, Davidow, Hall-Haro, & Frank, 2008; Johnson & Mason, 2002) and 3- to 4-month-olds use accretion and deletion of texture and boundary flow to segregate textured surfaces in depth (Johnson, 2000). Together, these results suggest that even very young infants use motion to parse surfaces in the depth plane (e.g., the percept of depth arises from the movement of the rod behind the occluder), to complete the structure of partly occluded objects (e.g., the percept of a single object arises from the relative motion of the visible portions of the rod.

Developmental scientists have also investigated infants' ability to extract the 3D shape of fully visible objects from motion-carried information. One investigative technique is to habituate infants to a videotape or projected shadow of a 3D object continuously moving, on alternating trials, around two different rotational axes (Kellman, 1984; Kellman & Short, 1987). Infants are then presented with test trials in which they see the same object and a novel object,on alternating trials, moving around a third (new) rotational axis. Longer looking to the novel than familiar object it is taken as evidence that infants extracted the 3D structure of the habituated object. Another (control) group of infants is tested using the same procedure except rather than seeing the objects move continuously, infants are presented with static views of the objects at successive points on the rotational axis. Results of these studies reveal that infants aged 4 months look longer at the novel than familiar test object under kinetic but not static viewing conditions, indicating that young infants extract sufficient information from optic flow (but not from successive static images) to form a 3D object percept. A variation of this approach involves presenting infants with real 3D objects under monocular viewing conditions (Owsley, 1983; Yonas et al., 1987). The same pattern of results emerges: 4-month-olds perceive 3D shape under kinetic but not static viewing conditions.

A limitation of the approach described above, as pointed out by Arterberry and Yonas (1988), is that displays containing real objects or 2D depictions of real objects also contain information about contour and intersection of lines. Figural information about shape is embedded in the stimuli, limiting the conclusions that one can draw about infants' use of motion-carried information, alone. One way to control for this confound is to use random-dot stimuli, which are created when randomly distributed dots are projected onto the surfaces of a simple geometric shape (e.g., cube or cylinder) that rotates around a 3-D axis. It is the coherent structure of the dots' motion that gives rise to the percept of a 3D shape, often referred to as shape-from-motion (SFM). When the dots' motions lack a coherent structure the percept is one of randomly moving dots, or random motion (RM). Research conducted with adults indicates that the mature visual system readily extracts a percept of 3D structure from SFM displays relatively early in the visual processing stream under a variety of conditions (e.g., Gilroy & Blake, 2004; Murray, Schrater, & Kersten, 2004; Tittle, Todd, Perotti, & Norman, 1995). Unfortunately, research conducted with infants is more limited. In one of the few published studies, Arterberry and Yonas (1988) habituated 4-month-olds to one of two SFM displays: a complete cube or an incomplete cube (the complete cube with a corner missing). In test trials infants were presented with the SFM display they saw in habituation (e.g., complete cube) and the other SFM display (e.g., incomplete cube) on alternating trials; in both cases the dots rotated on a new axis. The infants looked longer at the novel than familiar SFM display. A subsequent control study conducted by Arterberry (1992) confirmed that infants were responding on the basis of structural differences, and not simply to differential amounts of motion in the two displays (e.g., the dots in the "cut-out" portion of the incomplete cube covered less distance than those in the analogous location of the complete cube). Finally, younger 2-month-olds also show a novelty response but not until later in the test trials, suggesting that the younger infants found the task more challenging (Arterberry & Yonas, 2000).

A related context in which infants' capacity to extract structure from the coherent motion of dots has been explored is that of point-light displays. Extant research has shown that young infants are sensitive to human point-light displays in which the percept of a human walker is achieved by the movement of light points as though attached to the major joints of the human body (Pinto, 2006). For example, 3-month-old infants discriminate between point-light walkers moving normally and point-light walkers moving out-of-phase; 3-month-olds also discriminate between upright and inverted point-light walkers (Bertenthal, Proffitt, & Cutting, 1984; Pinto, 2006). In addition, there are changes during the first 9 months in infants' use of coherent motion to interpret point light displays. For example, when habituated to upright moving point-light walkers, both 6-month-olds and 9-month-olds will look significantly longer at the point-light walkers passing through a table than at the point-light walkers moving behind a table, suggesting that infants will bind form solidity to upright point-light walkers (but not inverted or scrambled point-light walkers; Moore, Goodwin, George, Axelsson, & Braddick, 2007). Furthermore, when 9-month-olds are habituated with point-light displays of moving animals (or vehicles), they will dishabituate to static pictures of vehicles (or animals), suggesting infants at this age successfully categorize using point-light movement in a transfer paradigm (Arterberry & Bornstein, 2002).

### *1.2. Present research*

The purpose of the present research was two-fold. First, we sought to provide converging evidence via a conceptual replication (Giner-Sorolla, 2012; Makel, Plucker, & Hegarty, 2012; Nosek, Spies, & Motyl, 2012) for the conclusion that even young infants can extract 3D object structure from optic flow alone. Second, to date all research investigating infants' use of motion-carried information to extract 3D object form has been conducted using habituation paradigms with young infants. Because our long-term goal is to investigate the neural basis of 3D object perception in infants using functional near-infrared spectroscopy (fNIRS), and habituation paradigms are not conducive to neuroimaging protocols (e.g., most

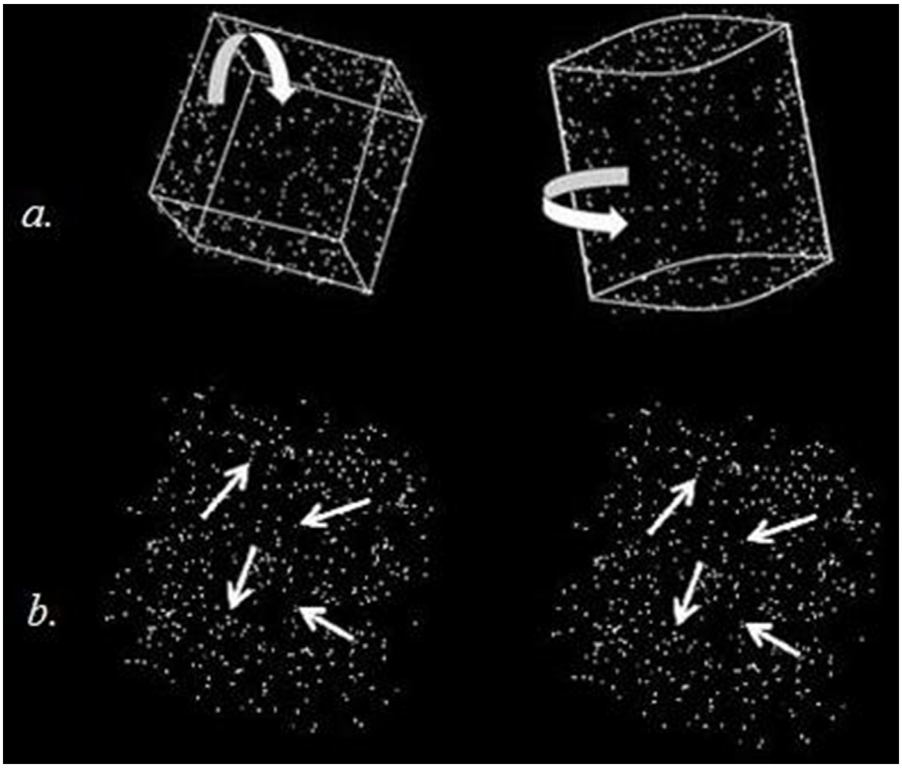


**Fig. 1.** Stimuli used in Experiments 1 and 2: (a) SFM cube and cylinder, respectively and (b) RM cube and cylinder, respectively. White outlines and arrows in the SFM stimuli illustrate perceived contour and motion but were not present in the display. White arrows in the RM stimuli illustrate direction of motion but were not present in the display.

data processing approaches assume trials of equal length), we were compelled to develop a fNIRS-friendly protocol. To this end, we used a familiarization/visual-paired-comparison (F/VPC) procedure that employed computer-controlled rather than infant-controlled trial termination criteria. In addition, we tested infants in two age ranges (4.5 months and 9 months) to provide corroborating evidence for the success of the paradigm and to allow us to explore potential age-related changes in infants' interpretation of SFM and RM displays.

Two experiments were conducted with infants mean age 4.5 and 9 months. In both experiments infants were first presented with SFM and RM displays (Fig. 1) on alternating trials. In the SFM display, coherent motion of the dots specified a 3D form (e.g., a cube). In the RM display the motion of the dots was randomly distributed (i.e., the dots moved at the same velocity as in the SFM display but the direction of the dots' motion was randomly assigned). RM trials were paired with SFM trials to allow us to assess whether infant visual scanning behaviors dissociate processing of dynamic displays that do, and do not, contain information about 3D shape. Such an outcome would allow one to predict, on the basis of familiarization data alone, whether infants extracted 3D shape from coherent motion. Finally, pilot data suggested that younger infants required more exposure to the SFM display to extract 3D shape. Hence younger infants were presented with 4 pairs, and older infants with 2 pairs, of SFM/RM trials.

Following familiarization trials infants were presented with two test trials in which the familiar SFM display was paired with a novel SFM display (e.g., cylinder). If infants extract 3D structure from coherent motion during the familiarization trials, they should look significantly longer at the novel than familiar SFM display in the test trials. Visual attention to and scanning of the familiarization and test displays was measured using a remote eye tracker.

## 2. Experiment 1

Infants' ability to extract 3D object structure from coherent motion displays was assessed using a familiarization/VPC procedure. Infants' aged 4.5 and 9 months were presented with 4 pairs (younger infants) or 2 pairs (older infants) of SFM/RM trials. Next, infants saw the SFM display viewed previously (e.g., cube) paired with the novel SFM display (e.g., cylinder). If infants' extract the 3D structure from the SFM display seen in the familiarization trials, they should look longer at the familiar than novel SFM display in the test trials. We also expected infants to differentially scan the SFM and RM displays seen in familiarization trials.

## 2.1. Method

### 2.1.1. Participants

Participants were 14 infants mean age 4 months 22 days (7 males, range 3 months 25 days to 5 months 27 days,) and 16 infants mean age 9 months 4 days (8 males, range 8 months 10 days to 9 months 25 days). Thirteen additional infants were tested but eliminated from the final sample because of fussiness ($N=9$) or failure to attend to the displays ($N=4$). Parents reported their infant's race/ethnicity as Caucasian ($N=22$), Hispanic ($N=4$), Asian ($N=0$), Black ($N=1$), American Indian ($N=2$) or mixed race ($N=1$). Infants and their parents were recruited primarily from commercially produced lists. The parents were offered $5 or a lab T-shirt for participation. The experimental procedure was explained to the parents and informed consent was obtained prior to testing.

### 2.1.2. Apparatus and data recording

A remote eye tracker (Tobii T60 XL) was used to measure eye movements during stimuli presentation. The infrared corneal reflection eye tracker was embedded in the lower portion of a 24 in flat screen monitor (17.7W TFT l flat screen monitor) (resolution: $1024 \times 768$ pixels) and detected the position of the pupil and the corneal reflection of the infrared light from both eyes. The Tobii T60 XL records data at 60 Hz with an average accuracy of 0.5° visual angle and a head movement compensation drift of **G**0.1. Fixation data were defined using the Tobii fixation filter (version 2.2.8) with a velocity threshold of 35 pixels and a distance threshold of 35 pixels. Total duration of looking during each test trial was calculated by the sum of fixation data for each trial. The monitor was mounted on an adjustable arm so that it could be positioned optimally for each infant. A Logitech Webcam Pro 9000 was placed directly below the monitor to record a full-face view of the infant during stimuli presentation. The stimuli were presented using professional visualization software (Tobii Studio) on a Dell Precision M6400 laptop computer with a Windows XP operating system.

### 2.1.3. Stimuli

The SFM and RM stimuli (Fig. 1) were adapted from Murray et al. (2004).[1] The SFM displays were composed of 450 white dots (against a black background) orthographically projected onto the surfaces of a simple geometric shape (cube or cylinder) that rotated 30° around a 3D axis during each 5 s trial. The cube rotated around the $x$-axis and the cylinder around the $y$-axis. The RM displays were composed of the same number of dots moving at the same velocity except that the direction of each dots' motion was randomly assigned. Each SFM and RM display was preceded by a static display composed of a fixed random-dot scrambled image. The static display was presented for another purpose and will not be discussed further. The familiarization stimuli (SFM and RM) were 15 cm × 13 cm and presented at the center of the screen. The SFM and RM stimuli seen in test were reduced to 10 × 8 viewed side-by-side, and centered on the screen.

### 2.1.4. Design

The younger infants saw four pairs and the older infants two pairs of SFM-RM trials. The 3D shape (cube or cylinder) seen in the familiarization trials and the order in which the SFM and RM displays were presented within each pair was counterbalanced across participants. Next, infants saw two 5 s test trials in which the SFM display seen in the familiarization trials was paired with the previously unviewed SFM display. The side (right or left) on which the familiar shape was presented on trial 1 was counterbalanced across infants and reversed for trial 2.

### 2.1.5. Procedure

Infants were seated in a parent's lap 65 cm away from the monitor on which the stimuli were presented. The testing room was dark and black curtains shielded the infant/parent from the rest of the testing room. Parents were instructed to close their eyes or look down during the test session. To obtain reliable and valid eye movement data the Tobii Studio infant calibration program was used prior to stimulus presentation. Animated stimuli were used to direct attention to five gaze positions covering over 80% of the viewing area.

### 2.1.6. Data coding

Number of fixations and duration of looking to the familiarization and test displays were both coded. However, because they yielded identical results only duration of looking will be reported.

One purpose of the current research was to identify visual scanning measures (besides duration of looking) that would differentiate between infants' processing of coherent and random motion displays. We hypothesized that infants would demonstrate more systemic scanning patterns to the coherent than random motion display. To test this hypothesis we computed two additional scanning measures to be used in the analysis of the familiarization data. Both measures were computed using fixation coordinates ($x$, $y$) for each look within each trial. The first measure we calculated was the distance from one fixation coordinate to the next (in pixels); we call this distance. The second measure we calculated was the angle between one fixation coordinate and the next (in degrees); we call this measure direction. We reasoned that if infants

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[1] We thank Dr. Scott Murray for making the SFM and RM stimuli used in Experiment 1 available to us.

**Table 1**
Infant means (standard deviations) in familiarization data.

| | Duration (in seconds) | | Distance (in pixels) | | Direction (in degree of angle) | |
|---|---|---|---|---|---|---|
| | SFM | RM | SFM | RM | SFM | RM |
| Experiment 1 | | | | | | |
| 4.5 month olds ($n = 14$) | 2.14 (0.96) | 2.33 (1.03) | 296.66 (97.80) | 289.97 (107.59) | 43.11 (6.34) | 42.59 (9.78) |
| 9 month olds ($n = 16$) | 1.93 (1.24) | 2.04 (1.16) | 276.05 (117.16) | 248.47 (124.16) | 36.92 (15.45) | 43.18 (17.14) |
| Experiment 2 | | | | | | |
| 4.5 month olds ($n = 20$) | 2.02 (1.03) | 2.35 (1.13) | 243.70 (110.33) | 311.12 (217.38) | 43.75 (7.90) | 40.81 (13.02) |
| 9 month olds ($n = 20$) | 2.38 (1.08) | 2.62 (1.20) | 251.29 (103.33) | 194.28 (79.37) | 45.54 (12.72) | 41.91 (15.21) |

perceived the 3D SFM shape, they would scan the moving contour of the shape in a systematic fashion. Previous research indicates that infants as young as 3.5 months scan directional surface information presented in random dot disparity displays (Fox, Aslin, Shea, & Dumais, 1980). In contrast, we predicted that viewing RM displays that do not possess moving contour would not elicit systematically distributed infant scanning. In short, we expected the distance and direction between looks to be smaller (i.e., directed at local contour rather than randomly distributed across the display) when infants viewed the SFM than RM displays.

### 2.2. Results

#### 2.2.1. Preliminary analyses

Preliminary analysis of the familiarization data, for both age groups, revealed no significant main effects or interactions involving order of stimulus presentation (SFM or RM first), the shape seen during familiarization trials (cube or cylinder), pair number (1, 2, 3, 4 for younger infants and 1, 2 for older infants), or sex on looking times. Hence, the familiarization data were collapsed across these factors (Table 1).

Percent-to-novel (%-N) scores were computed for each test trial by dividing the time infants looked to the novel shape by the time infants looked to the novel and familiar shape combined. Preliminary analysis of %-N scores, for both age groups, revealed no significant main effects or interactions involving novel shape (cube or cylinder), side on which the novel stimulus was first presented (right or left), or sex on looking times. Hence, the test data were collapsed across these factors. Preliminary analyses did reveal a significant main effect of trial for both age groups so the data were not collapsed across trials. Of the 28 possible test trials obtained with the younger infants (14 infants $\times$ 2 trials) one data point was missing. Of the 32 possible test trials obtained with the older infants (16 infants $\times$ 2 trials) five data points were missing. In order to maintain the full data set for all analyses, missing data points were replaced with the mean of their group. For comparison purposes, mean looking to the familiar and novel shape in each test trial along with corresponding %-N scores, before mean substitution, are reported (Table 2). The same results were obtained with and without mean substitution.

#### 2.2.2. Familiarization analyses

Infants' mean total duration of looking to the SFM and RM displays (Table 1) were analyzed using paired *t*-tests (two-tailed), for the younger and older infants separately. There were no significant differences in mean looking to the SFM and RM stimuli for the younger, $t(13) = -0.76$, $p > 0.05$, Cohen's $d = 0.42$, and older, $t(15) = -2.80$, $p > 0.05$, Cohen's $d = 1.45$, infants.

Infants' mean distance and direction between looks were analyzed in the same manner as mean duration of looking. For the younger infants, there were no significant differences in distance or direction between looks when viewing the SFM and RM stimuli, $t(13) = 0.19$, $p > 0.05$, Cohen's $d = 0.11$ and $t(13) = 0.22$, $p > 0.05$, Cohen's $d = 0.12$, respectively. For the older infants, there were no significant differences in distance or direction between looks when viewing the SFM and RM stimuli, $t(15) = 0.57$, $p > 0.05$, Cohen's $d = 0.29$ and $t(15) = -1.50$, $p > 0.05$, Cohen's $d = 0.77$, respectively.

**Table 2**
Infant means (standard deviations) in test data. Note that scores displayed in table are prior to mean substitution of missing data points (see text).

| | Test 1 | | | Test 2 | | |
|---|---|---|---|---|---|---|
| | Novel | Familiar | %-Novel | Novel | Familiar | %-Novel |
| Experiment 1 | | | | | | |
| 4.5 month olds ($n = 14$) | 1.35 (1.41) | 0.33 (0.41) | 0.80 (0.21) | 0.69 (0.63) | 1.23 (1.22) | 0.35 (0.27) |
| 9 month olds ($n = 16$) | 0.85 (0.92) | 0.46 (0.86) | 0.79 (0.27) | 0.66 (0.99) | 1.02 (1.21) | 0.30 (0.34) |
| Experiment 2 | | | | | | |
| 4.5 month olds ($n = 20$) | 0.81 (0.81) | 0.68 (0.92) | 0.64 (0.30) | 0.47 (0.80) | 0.91 (0.99) | 0.39 (0.39) |
| 9 month olds ($n = 20$) | 1.21 (1.18) | 0.43 (0.58) | 0.74 (0.31) | 1.01 (1.16) | 0.72 (1.04) | 0.59 (0.38) |

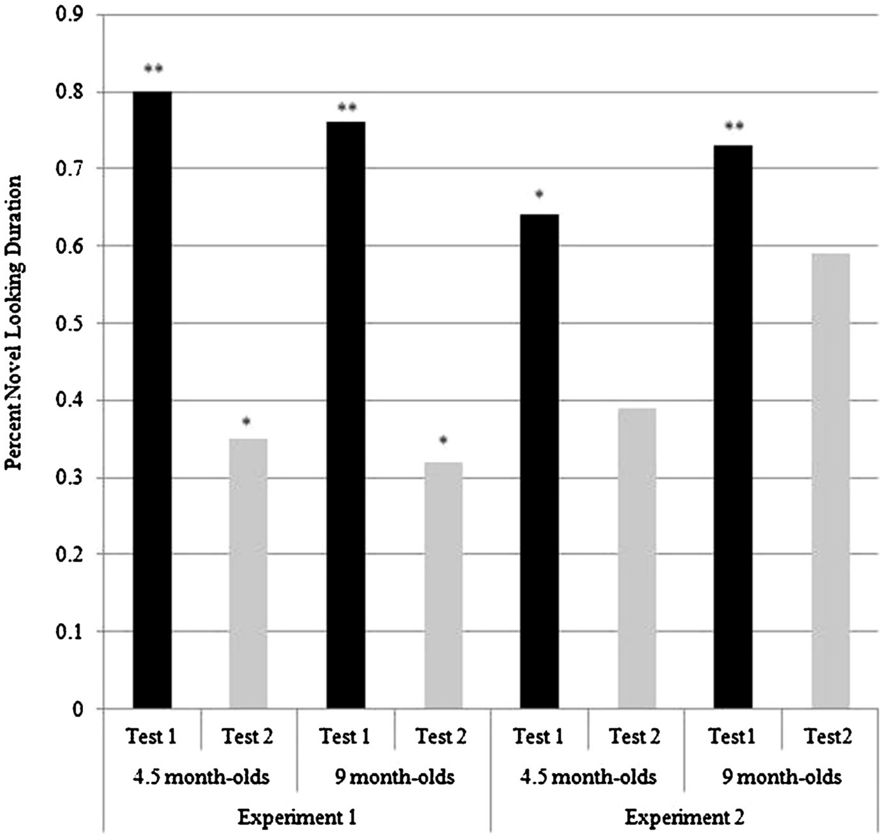


**Fig. 2.** Percent-to-novel scores, by age and trial, for Experiments 1 and 2. Asterisks indicate that %-novel score differed significantly from chance ($^{*}p < 0.05$ and $^{**}p < 0.01$).

Additional analyses were conducted to assess the effect of age on looking behavior during the familiarization trials. A mixed-model ANOVA was computed for each of the dependent variables (duration of looking, distance between looks, and direction of looks) with Age (4-month-olds, 9-month-olds) as the between-subjects factor and Display (SFM and RM) as the within-subjects factor. The main effects of Age and Display, and the Age × Display interaction, failed to reach significance for any of the three analyses (duration of looking, $F(1, 28) = 0.56$, $F(1, 28) = 0.40$, and $F(1, 28) = 0.03$ for Age, Display, and Age × Display respectively; distance between looks, $F(1, 28) = 1.27$, $F(1, 28) = 0.31$, and $F(1, 28) = 0.12$ for Age, Display, and Age × Display respectively; and direction of looks, $F(1, 28) = 0.46$, $F(1, 28) = 1.33$, and $F(1, 28) = 1.85$ for Age, Display, and Age × Display respectively).

### *2.2.3. Test analyses*

Infants' mean %-N scores (Fig. 2) for trial 1 (T1) and trial 2 (T2) were compared to chance (50%) using one-sample t-tests (two-tailed). For the younger infants, the mean %-N score obtained in T1 was above chance, $t(13) = 5.21$, $p < 0.001$, Cohen's $d = 2.89$, and in T2 was below chance, $t(13) = -2.14$, $p = 0.052$, Cohen's $d = 1.87$. The number of infants who had %-N scores > 50% were 12/14 (binomial $p = 0.006$) and 1/14 (binomial $p = 0.002$) for T1 and T2, respectively. Similar results were obtained with the older infants. The mean %-N score obtained in T1 was above chance, $t(15) = 4.50$, $p < 0.001$, Cohen's $d = 2.32$, and in T2 was below chance, $t(15) = -2.16$, $p = 0.047$ Cohen's $d = 1.14$. The number of infants who had %-N scores > 50% were 14/16 (binomial $p = 0.003$) and 4/16 (binomial $p = 0.03$) for T1 and T2, respectively.

An additional analysis was conducted to assess the effect of age on looking behavior during the trials. A mixed-model ANOVA was computed for %-Novel scores with Age (4-month-olds, 9-month-olds) as the between-subjects factor and Trial (1, 2) as the within-subjects factor. There was no significant main effect of Age, $F(1, 28) = 0.42$, $p > 0.05$. There was a significant main effect of Trial such that both age groups had higher %-Novel scores on T1, $F(1, 28) = 28.42$, $p < 05$, Cohen's $d = 1.70$. The Age × Trial interaction was not significant, $F(1, 28) = 0.01$, $p > 0.05$.

### 2.3. Discussion

Analysis of infants' scanning patterns during the familiarization phase of the experiment, including duration of looking, length of scan patterns, and direction of scan patterns, revealed no significant difference in scanning of the SFM and RM displays. Length and direction of scanning patterns were exploratory measurements and, contrary to our predictions, did not differentiate scanning of SFM and RM displays.

Both age groups demonstrated a robust preference for the novel form on T1, suggesting that the infants extracted the 3D form from the coherent motion display seen in the familiarization phase and recognized the previously unviewed form as novel. Unexpectedly, the infants demonstrated a preference for the familiar, rather than the novel, form on T2. Familiarity preferences, like novelty preferences, are taken as evidence that infants discriminated between two stimuli, but the processes that underlie familiarity and novelty preferences are thought to differ (Cohn, 2004; Houston-Price & Nakai, 2004). Before we engage further in this discussion however, one aspect of the experimental design needs to be addressed.

Recall that the cube rotated on the *x*-axis and the cylinder on the *y*-axis. Consequently, in the test trials the novel display differed from the familiar display in two ways: shape and axis of rotation. Hence, it is unclear whether the infants were responding to the novel shape or to the novel shape and the novel rotational axis. (It is unlikely that infants were responding to the novel rotational axis, alone, because rotational axis is perceived only with the emergence of a shape percept.) Experiment 2 tested these two hypotheses by having each test display differ from the familiarization display on one of two dimensions: axis of rotation or shape of object.

## 3. Experiment 2

Infants were tested using a procedure similar to that of Experiment 1 except that in the test trials infants saw the familiar shape rotating on a novel axis paired with the novel shape rotating on a familiar rotational axis.

### 3.1. Method

#### 3.1.1. Participants

Participants were 20 infants mean age 4 months 26 days (11 males, range 3 months 21 days to 5 months 27 days) and 20 infants mean age 9 months 3 days (10 males, range 8 months 29 days to 9 months 26 days). Fourteen additional infants were tested but eliminated from the final sample because of fussiness ($N = 11$) or failure to attend to the displays ($N = 3$). Parents reported their infant's race/ethnicity as Caucasian ($N = 30$), Hispanic ($N = 6$), Asian ($N = 0$), Black ($N = 1$), or mixed race ($N = 3$).

Participant recruitment was identical to that of Experiment 1.

#### 3.1.2. Materials, design, procedure

The SFM and RM stimuli were created using a custom-made graphical user interface[2] and were similar to the SFM and RM stimuli of Experiment 1 with one main difference: rotational axis was crossed with shape to create four stimuli: cube rotating on *x*-axis, cube rotating on *y*-axis, cylinder rotating on *x*-axis and cylinder rotating on *y*-axis.

### 3.2. Results

#### 3.2.1. Preliminary analyses

Preliminary analyses similar to those reported in Experiment 1 were conducted. No significant main effects or interactions emerged except for that of trial (T1 or T2) in the test data.

Of the 40 possible test trials obtained with each age group (20 infants × 2 trials), five and four data points were missing for the younger and older infants, respectively. Missing data points were replaced with the mean of their group. Mean looking to the familiar and novel shape and corresponding %-N scores, before mean substitution, are presented in Table 1. The same results were obtained with and without mean substitution.

#### 3.2.2. Familiarization analyses

Mean looking times to the SFM and RM displays (Table 2) were analyzed as in Experiment 1. There were no significant differences in looking times to SFM and RM stimuli for the younger, $t(19) = -1.42$, $p > 0.05$, Cohen's $d = 0.65$, or older, $t(19) = -0.87$, $p > 0.05$, Cohen's $d = 0.40$, infants.

Mean distance and direction between looks were analyzed as in Experiment 1. For the younger infants, there were no significant differences in distance or direction between looks to SFM and RM stimuli, $t(19) = -1.27$, $p > 0.05$, Cohen's $d = 0.58$ and $t(19) = 0.78$, $p > 0.05$, Cohen's $d = 0.36$, respectively. For the older infants, there were no significant differences in distance or direction between looks to SFM and RM stimuli, $t(19) = 1.81$, $p > 0.05$, Cohen's $d = 0.83$ and $t(19) = 0.88$, $p > 0.05$, Cohen's $d = 0.40$, respectively.

[2] We thank Dr. David A. Boas for designing the graphical user interface to create the SFM and RM stimuli used in Experiment 2.

An additional analysis was conducted to assess the effect of age on looking behavior during the familiarization trials. A mixed-model ANOVA was computed for each of the dependent variables (duration of looking, distance between looks, and direction of looks) with Age (4-month-olds, 9-month-olds) as the between-subjects factor and Display (SFM, RM) as the within-subjects factor. The main effects of Age and Display, and the Age × Display interaction, failed to reach significance for any of the three analyses (duration of looking, $F(1, 38) = 1.09$, $F(1, 38) = 2.46$, and $F(1, 38) = 0.05$ for Age, Display, and Age × Display respectively; distance between looks, $F(1, 38) = 0.09$, $F(1, 38) = 0.03$, and $F(1, 38) = 4.06$, for Age, Display, and Age × Display respectively; and direction of looks, $F(1, 38) = 0.27$, $F(1, 38) = 1.39$, and $F(1, 38) = 0.02$ for Age, Display, and Age × Display respectively).

#### *3.2.3. Test analyses*

Infants' mean %-N scores (Fig. 2) were analyzed as in Experiment 1. For the younger infants, the mean %-N score obtained in T1 was above chance, $t(19) = 2.29$, $p = 0.034$, Cohen's $d = 1.05$. In T2 the %-N score was below chance but the effect size was less robust, $t(19) = -1.36$, $p = 0.190$, Cohen's $d = 0.624$,. The number of infants who had %-N scores > 50% were 16/20 (binomial $p = 0.005$) and 7/20 (binomial $p = 0.074$) for T1 and T2, respectively.

For the older infants, the mean %-N score obtained in T1 was above chance, $t(19) = 3.75$, $p = 0.001$, Cohen's $d = 1.721$. The mean %-N score obtained in T2 was also above chance but the effect size was small, $t(19) = 1.05$, $p = 0.308$, Cohen's $d = 0.483$. The number of infants who had %-N scores > 50% were 18/20 (binomial $p < 0.001$) and 14/20 (binomial $p = 0.037$) for T1 and T2, respectively.

An additional analysis was conducted to assess the effect of age on looking behavior during the trials. A mixed-model ANOVA was computed for %-Novel scores with Age (4-month-olds, 9-month-olds) as the between-subjects factor and Trial (1, 2) as the within-subjects factor. There was a significant main effect of Age such that 9-month-olds had significantly higher %-Novel scores than 4-month-olds across test trials, $F(1, 38) = 4.36$, $p < 0.05$, Cohen's $d = 0.28$. There was a significant main effect of Trial such that both age groups had higher %-Novel scores on T1, $F(1, 38) = 6.32$, $p < 0.05$, Cohen's $d = 0.59$. There was no significant Age × Trial interaction, $F(1, 38) = 0.55$, $p > 0.05$.

#### *3.2.4. Comparison of Experiment 1 and Experiment 2*

To assess whether infants' test performance in Experiment 2 differed significantly from that of Experiment 1, the %-N scores (for each age group separately) were subjected to a repeated-measures analysis of variance with Experiment (1 or 2) as the between-subjects factor and Trial (T1 or T2) as the within-subjects factor. For both age groups the only significant effect was the main effect of trial: younger infants, $F(1,32) = 20.87$, $p < 0.001$, $d = 0.395$, and older infants, $F(1,34) = 11.22$, $p = 0.002$, $d = 0.248$.

### *3.3. Discussion*

Analysis of infants' scanning patterns during the familiarization phase of the experiment, including duration of looking, length of scan patterns, and direction of scan patterns, revealed no significant difference in scanning of the SFM and RM displays.

Also as in Experiment 1, infants in both age groups evidenced a significant novelty preference on T1 and these %-N scores did not differ reliably from those obtained in Experiment 1. Hence, even when we controlled for rotational axis the infants still demonstrated a novelty preference on T1. In contrast, neither age group showed a strong familiarity or novelty preference on T2 (the younger infants tended to look longer at the familiar display whereas the older infants tended to look longer at the novel display). Apparently, making the task more difficult - both test displays differed from the familiarization display, one in shape and the other in rotational axis - led infants away from a strong familiarity preference on T2. However, as in Experiment 1, infants' response on T1 and T2 still differed significantly from each other.

## **4. General discussion**

The present research explored infants' capacity to extract 3D object shape from coherent motion displays using a F/VPC procedure. The results provided converging evidence, using a different paradigm, for the conclusion drawn by Arterberry and Yonas (1988, 2000) that even young infants extract 3D object structure from motion-carried information. Remarkably, a novelty preference for the familiar 3D form was observed with very little prior exposure to the coherent motion displays: 4.5-month-olds saw 4 SFM familiarization trials (5 s each) and 9-month-olds saw only 2 trials (5 s each). This is much less exposure than used by Arterberry and Yonas (1988, 2000) who fully habituated 4-month-olds to coherent motion displays prior to test. Furthermore, infants recognized the previously viewed form regardless of whether it differed from the novel form in shape and rotational axis (Experiment 1) or shape alone (Experiment 2). Although robust age-related differences were not observed, it is possible that such differences would have emerged if the younger infants, like the older infants, had been presented with only two familiarization trials.

Unexpectedly, trial effects emerged. In Experiment 1, both age groups showed a strong novelty preference on T1 and a strong familiarity preference on T2. Familiarity preferences are thought to reflect incomplete encoding of a visual stimulus and are typically observed when the stimulus is more complex or the task more demanding (Moore & Johnson, 2011; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982). If infants are given more time to encode the stimulus, familiarity preferences are replaced by novelty preferences (Moore & Johnson, 2011; Roder, Bushnell, & Sasseville, 2000; Rose et al., 1982). In the present experiment, however, the novelty preference preceded the familiarity preference. Although unusual, this pattern has been observed previously (e.g., Fisher-Thompson & Peterson, 2004). One possible explanation for this result is that after detecting and attending to the novel coherent motion display in the first test trial, infants engaged in further processing of the familiar coherent motion display in the second test trial, seeking to identify potential ways (besides shape) in which the two displays differed from one another. The familiarity preference became a null preference when the task was made more difficult – when both test stimuli differed from the familiarization stimuli (one in shape and one in rotational axis), lending credence to this hypothesis. Of course, this is only speculative and further research is needed to examine the attentional and/or perceptual processes that underlie this response.

A number of visual attention measures, including duration of looking, scan length, and direction of scan, were coded and used to assess infants' attention to and scanning of the SFM and RM displays. Infants' response to the SFM and RM displays did not differ significantly on any of the behavioral measures. Contrary to our predictions, moving-dot displays that give rise to the percept of a shape, as compared to those that do not, fail to elicit different scanning patterns, at least as measured here. Previous research indicates that infants 7 months of age discriminate between displays containing coherent and random motion (Spitz, Stiles, & Siegel, 1993). In the current research we were hoping to identify distinct patterns of scanning associated with coherent and random motion displays. Further investigation is needed to identify the extent to which other visual behaviors, such as pupil dilation, can be used to dissociate processing of SFM and RM displays (Laeng, Sirois, & Gredeback, 2012; Sirois & Jackson, 2012).

Finally, one purpose of the present research was to develop a F/VPC behavioral paradigm to assesses infants' visual scanning and perception of SFM and RM displays that can be used in conjunction with fNIRS. In a pilot study, we assessed cortical responses to SFM and RM stimuli, with the hypothesis that SFM and RM displays would elicit different patterns of neural activation in occipital–parietal and occipital–temporal object processing areas. Preliminary analysis of the data suggested that processing of SFM and RM displays does elicit distinct patterns of neural activation in these areas, but that cortical responses are more anterior and bi-lateral in older than younger infants (Hirshkowitz & Wilcox, 2012). Further investigation is needed to identify if these patterns as measured by fNIRS are robust. Regardless, this research places us on a path to study brain–behavior relations in the development of 3D object perception during infancy.

In conclusion, we have firmly established that younger and older infants' use common motion of randomly distributed dots to extract structure of a complete object in 3D space. The charge of future research is to identify the conditions under which coherent motion gives rise to 3D percepts and the neural mechanisms that underlie this early emerging capacity.

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## References

Arterberry, M. E. (1992). Infants' perception of three-dimensional shape specified by motion-carried information. *Bulletin of the Psychonomic Society: 30.*, (4), 337–339.

Arterberry, M. E., & Bornstein, M. H. (2002). Infant perceptual and conceptual categorization: The roles of static and dynamic stimulus attributes. *Cognition: 86.*, (1), 1–24.

Arterberry, M. E., Craton, L. G., & Yonas, A. (1993). Infants' sensitivity to motion-carried information for depth and object properties. In C. E. Granrud (Ed.), *Visual perception and cognition in infancy* (pp. 215–234). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Arterberry, M., & Yonas, A. (1988). Infants' sensitivity to kinetic information for three-dimensional object shape. *Perception and Psychophysics: 44.*, (1), 1–6.

Arterberry, M., & Yonas, A. (2000). Perception of three-dimensional shape specified by optic flow by 8-week-old infants. *Perception and Psychophysics: 62.*, (3), 550–556.

Bertenthal, B. I., Proffitt, D. R., & Cutting, J. E. (1984). Infant sensitivity to figural coherence in biomechanical motions. *Journal of Experimental Child Psychology: 37.*, (2), 213–230.

Cohn, L. (2004). Uses and misuses of habituation and related preference paradigms. *Infant and Child Development: 13.*, 349–352.

Fisher-Thompson, D., & Peterson, J. A. (2004). Infant side biases and familiarity–novelty preferences during a serial paired-comparison task. *Infancy: 5.*, (3), 309–340.

Fox, R., Aslin, R. N., Shea, S. L., & Dumais, S. T. (1980). Stereopsis in human infants. *Science: 207.*, 323–324.

Gilroy, L., & Blake, R. (2004). Physics embedded in visual perception of three-dimensional shape from motion. *Nature Neuroscience: 7.*, (9), 921–923.

Giner-Sorolla, R. (2012). Science or art? How aesthetic standards grease the way through the publication bottleneck but undermine science. *Perspectives on Psychological Science: 7.*, (6), 562–571.

Hirshkowitz, A., & Wilcox, T. (2012). Object perception in infancy: A NIRS study. In *Poster presented at the biennial meeting of International Conference of Infant Studies in Minnesota, MN*.

Houston-Price, C., & Nakai, S. (2004). Distinguishing novelty and familiarity effects in infant preference procedures. *Infant and Child Development: 13.*, 341–348.

Johnson, S. (2000). The development of visual surface perception. In C. Rovee-Collier, L. Lipsitt, & H. Hayne (Eds.), *Progress in infancy research, vol. 1* (pp. 113–154). Mahwah, NJ, USA: Lawrence Erlbaum Associates Publishers.

Johnson, S. (2004). Development of perceptual completion in infancy. *Psychological Science: 15.*, (11), 769–775.

Johnson, S., Davidow, J., Hall-Haro, C., & Frank, M. (2008). Development of perceptual completion originates in information acquisition. *Developmental Psychology: 44.*, (5), 1214–1224.

Johnson, S., & Mason, U. (2002). Perception of kinetic illusory contours by two-month-old infants. *Child Development: 73.*, (1), 22–34.

Kellman, P. J. (1984). Perception of three-dimensional form by human infants. *Perception and Psychophysics: 36.*, (4), 353–358.
Kellman, P., & Spelke, E. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology: 15.*, 483–524.
Kellman, P., & Short, K. (1987). Development of three-dimensional form perception. *Journal of Experimental Psychology: 13.*, (4), 545–557.
Laeng, B., Sirois, S., & Gredeback, G. (2012). Pupillometry: A window to the preconscious? *Perspectives on Psychological Science: 7.*, (1), 18–27.
Makel, M., Plucker, J., & Hegarty, B. (2012). Replications in psychology research: How often do they really occur? *Perspectives on Psychological Science: 7.*, (6), 537–542.
Moore, D. G., Goodwin, J. E., George, R., Axelsson, E. L., & Braddick, F. M. B. (2007). Infants perceive human point-light displays as solid forms. *Cognition: 104.*, (2), 377–396.
Moore, D., & Johnson, S. (2011). Mental rotation of dynamic, three-dimensional stimuli by 3-month-old infants. *Infancy: 16.*, (4), 435–445.
Murray, S., Schrater, P., & Kersten, D. (2004). Perceptual grouping and the interactions between visual cortical areas. *Neural Networks: 17.*, 695–705.
Nosek, B., Spies, J., & Motyl, M. (2012). Scientific utopia: II. restructuring incentives and practices to promote truth over publishability. *Perspectives on Psychological Science: 7.*, (6), 615–631.
Owsley, C. (1983). The role of motion in infants' perception of solid shape. *Perception: 12.*, (6), 707–717.
Pinto, J. (2006). *Developing body representations: A review of infants' responses to biological-motion displays*. pp. 305–322. New York, NY: Oxford University Press.
Roder, B. J., Bushnell, E. W., & Sasseville, A. M. (2000). Infants' preferences for familiarity and novelty during the course of visual processing. *Infancy: 1.*, 491–507.
Rose, S. A., Gottfried, A. W., Melloy-Carminar, P., & Bridger, W. H. (1982). Familiarity and novelty preferences in infant recognition memory: Implications for information processing. *Developmental Psychology: 18.*, 704–713.
Sirois, S., & Jackson, I. (2012). Pupil dilation and object permanence in infants. *Infancy: 17.*, (1), 61–78.
Spitz, R., Stiles, J., & Siegel, R. (1993). Infant use of relative motion as information for form: Evidence for spatiotemporal integration of complex motion displays. *Perception & Psychophysics: 53.*, (2), 190–199.
Tittle, J., Todd, J., Perotti, V., & Norman, F. (1995). Systematic distortion of perceived three-dimensional structure from motion and binocular stereopsis. *Journal of Experimental Psychology: 21.*, (3), 663–678.
Yonas, A., Arterberry, M., & Granrud, C. (1987). Four-month-old infants' sensitivity to binocular and kinetic information for three-dimensional-object shape. *Child Development: 58.*, 910–917.